Magnetically Damped Furnace
Bitter Magnet Coil 1

FINAL REPORT

M. D. Bird
INTRODUCTION

A magnet has been built by the National High Magnetic Field Laboratory for NASA on a cost reimbursement contract. The magnet is intended to demonstrate the technology and feasibility of building a magnet for space based crystal growth. A Bitter magnet (named after Francis Bitter, its inventor) was built consisting of four split coils electrically in series and hydraulically in parallel. The coils are housed in a steel vessel to reduce the fringe field and provide some on-axis field enhancement. The steel was nickel plated and Teflon coated to minimize interaction with the water cooling system. The magnet provides 0.14 T in a 184 mm bore with 3 kW of power.

TEST PROCEDURE AND DATA

I MASS

Maximum mass of magnet empty: 100 kg
Measured mass of magnet empty: 77 kg
Measured mass of magnet full: 79 kg
Measured by: O’Reilly, Loffelbein
Equipment Used: Pelouze Model 4040 400 lb Capacity Digital Scale +/- 0.2 kg

II STRUCTURAL AND MECHANICAL

<table>
<thead>
<tr>
<th>Acceleration (g’s)</th>
<th>(m/s^2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>13.6</td>
<td>133.416</td>
</tr>
</tbody>
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SPRING FORCES

<table>
<thead>
<tr>
<th>Desired Clamping force (N)</th>
<th>2000</th>
</tr>
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<tbody>
<tr>
<td>Spring stiffness (N/mm)</td>
<td>21.3</td>
</tr>
<tr>
<td>Spring free length (mm)</td>
<td>7.94</td>
</tr>
<tr>
<td>Spring solid height (mm)</td>
<td>4.9</td>
</tr>
<tr>
<td>Max. spring displacement (mm)</td>
<td>3.04</td>
</tr>
<tr>
<td>Max. spring force/spring (N)</td>
<td>64.8</td>
</tr>
<tr>
<td># of springs</td>
<td>50</td>
</tr>
<tr>
<td>Max. spring force/coil (N)</td>
<td>3238</td>
</tr>
<tr>
<td>Max. spring force tot (N)</td>
<td>12950</td>
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COIL MASSES AND G FORCES

<table>
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<tr>
<th>Coil #</th>
<th>1</th>
<th>2</th>
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<th>4</th>
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</thead>
<tbody>
<tr>
<td>coil mass (kg)</td>
<td>7.4</td>
<td>9</td>
<td>11.2</td>
<td>15.2</td>
</tr>
<tr>
<td>Accel. Force (N)</td>
<td>987</td>
<td>1201</td>
<td>1494</td>
<td>2028</td>
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<tr>
<td>Total mass (kg)</td>
<td>42.8</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total force (N)</td>
<td>5710</td>
<td></td>
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HYDRAULIC FORCES
Water Pressure (MPa) 0.02
Head area (mm^2) 65182
Pressure load (N) 1304

DESIGN FORCE
Design force (N) 14254

STAND-OFF ROD COMPRESSION
length (mm) 53
diameter of rods (mm) 5
number of rods 24
area (mm^2) 471
Stress (MPa) 30
Yield stress (MPa) 210
Safety factor 6.9

HEAD DEFLECTION: see Roark's formulas for stress and strain pg. 405
Outer radius a (mm) 172
Inner radius b (mm) 94
Thickness t (mm) 7
Young's modulus E (MPa) 2.10E+05
Poisson's ratio nu 0.30
Bending stiffness D 6.60E+06
distributed load q (MPa) 2.19E-01

C1 0.4392
C7 0.5839
C4 0.9957
L11 0.0014
L14 0.0118
L17 0.0768

Displacement at inner radius

simple support
yb (mm) 1.64
thetb(rad) 0.02
theta(rad) 0.02

clamped
yb (mm) 0.11

Displacement at inner radius
Moment at outer radius Mra (N) -452
Stress at outer radius Sra (MPa) -55.4
Yield Stress Sy (MPa) -210
safety factor 3.79
VESSEL SHELL TENSION
vessel section (mm^2) 5404
vessel Sss (MPa) 2.64
vessel strain 1.26E-05
vessel length (mm) 218
vessel DL (mm) 0.27
yield stress (MPa) 210
safety factor 8.0

SCREW TENSION
screw section (mm^2) 14.2
# of screws 18
total moment at outer radius (Nmm) -488761
moment per screw (Nmm) -27153
moment arm (mm) 6.25
screw tension (N) 4345
proof load (N) 8230
safety factor 1.89

III MATERIAL COMPATIBILITY

A complete drawing package was sent to NASA and was approved before construction began. A package of as-built drawings is enclosed. Materials in contact with coolant consist of the following: stainless steel, nickel, Teflon, Kapton.

IV. DIMENSIONS

<table>
<thead>
<tr>
<th></th>
<th>Required</th>
<th>Measured</th>
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<tbody>
<tr>
<td>Length</td>
<td>238.1 mm max.</td>
<td>239.44, 239.58 mm</td>
</tr>
<tr>
<td>Inside diameter</td>
<td>184.2 mm min.</td>
<td>184.24, 184.26 mm</td>
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<tr>
<td>Outside diameter</td>
<td>361.95 mm max.</td>
<td>341.78, 341.42 mm</td>
</tr>
<tr>
<td>Measured by:</td>
<td>Bird, O'Reilly</td>
<td></td>
</tr>
<tr>
<td>Equipment used:</td>
<td>Mitutoyo 0-55 cm caliper</td>
<td></td>
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V. FIELD STRENGTH AND HOMOGENEITY

The water flow through the magnet was set at 640 ml/10 sec (230 kg/hr) as measured with a graduated cylinder and stopwatch. The current was set at 20.88, 27.87 and 31.86 Amps as measured by a shunt and multimeter. The voltage across the coil was measured at 52.28, 76.80 and 92.99 Volts for the three current settings, respectively. The electrical power consumed during the three measurements was 1092, 2140, and 2963 Watts, respectively. The field was mapped along the axis of the magnet using a Hall probe, Hall probe holder, and gaussmeter. The recorded data follows:
<table>
<thead>
<tr>
<th>pos. (mm)</th>
<th>1 kW Field (mT)</th>
<th>2 kW Field (mT)</th>
<th>3 kW Field (mT)</th>
</tr>
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<tbody>
<tr>
<td>49</td>
<td>76.5</td>
<td>105.9</td>
<td>124.4</td>
</tr>
<tr>
<td>64</td>
<td>81.3</td>
<td>112.6</td>
<td>131.8</td>
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<tr>
<td>79</td>
<td>83.9</td>
<td>116.2</td>
<td>135.3</td>
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<tr>
<td>94</td>
<td>84.8</td>
<td>117.6</td>
<td>136.5</td>
</tr>
<tr>
<td>109</td>
<td>85.1</td>
<td>118.0</td>
<td>136.4</td>
</tr>
<tr>
<td>124</td>
<td>85.5</td>
<td>118.4</td>
<td>136.4</td>
</tr>
<tr>
<td>139</td>
<td>86.1</td>
<td>119.0</td>
<td>136.8</td>
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<tr>
<td>154</td>
<td>86.6</td>
<td>119.5</td>
<td>136.9</td>
</tr>
<tr>
<td>169</td>
<td>86.1</td>
<td>118.7</td>
<td>135.4</td>
</tr>
<tr>
<td>184</td>
<td>83.7</td>
<td>115.2</td>
<td>130.9</td>
</tr>
<tr>
<td>199</td>
<td>78.4</td>
<td>107.9</td>
<td>122.4</td>
</tr>
</tbody>
</table>

1 kW Field Profile
Field variation over 150 mm: 1 kW = 8.2%, 2 kW = 11.4%, 3 kW = 9.1%. Specification: < 10 % at 3 kW.
Equipment used: ABB/Alpha Scientific 20kA, 500 V power supply; Weston KS9442-L6 150 A, 50 mV shunt; Keithley 2001 Multimeter (2), Lakeshore 420 Gaussmeter; Lakeshore MMA-2502-VG axial metal stem Hall probe; NHMFL RES/TOL-1 hall probe holder, Kartell, 1000 mL graduated cylinder; Fischer-Scientific Digital Dual Channel Thermometer; Micronta 63-5012 LCD electronic stopwatch

VI. POWER

See item V.

VII. ELECTRICAL ISOLATION

Required line to chassis isolation: 2 Megohms
Measured line to chassis isolation: 500 Megohms at 500 V
Equipment used: AEMC model 1000 Megohmmeter

VII. PHYSICAL POWER INTERFACE

The MDF-BC1 provides screw lug connectors capable of utilizing 8 gage wire within the zone shown in Figure 3.1.3-1 of the MDF-BC1 specifications.

VIII. COOLANT LOOP PHYSICAL CONNECTIONS

Fluid connectors are male 37 degree flare fittings size 6 per commercial equivalent of military standard 3365.

IX. INLET/OUTLET TEMPERATURE OF MDF-BC1 COOLANT

Set flow at 232 kg/hr. and measure temperature rise at 1, 2 and 3 kW.

<table>
<thead>
<tr>
<th>I (Amps)</th>
<th>V (Volts)</th>
<th>Tin (C)</th>
<th>Tout (C)</th>
<th>Q (kg/hr.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>20.88</td>
<td>52.28</td>
<td>12.4</td>
<td>13.3</td>
<td>230</td>
</tr>
<tr>
<td>27.87</td>
<td>76.80</td>
<td>12.5</td>
<td>15.5</td>
<td>230</td>
</tr>
<tr>
<td>31.86</td>
<td>92.99</td>
<td>12.6</td>
<td>19.4</td>
<td>230</td>
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</tbody>
</table>

Performed by: Bird, Bole, Loffelbein, O'Reilly
Equipment used: see V
X. COOLANT FLOW RATE/ PRESSURE DROP

<table>
<thead>
<tr>
<th>Flow (mL/10s)</th>
<th>Flow (kg/hr)</th>
<th>DP (psi)</th>
<th>DP (kPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>510</td>
<td>184</td>
<td>1.2</td>
<td>8</td>
</tr>
<tr>
<td>610</td>
<td>220</td>
<td>1.5</td>
<td>10</td>
</tr>
<tr>
<td>630</td>
<td>227</td>
<td>2.0</td>
<td>14</td>
</tr>
<tr>
<td>700</td>
<td>252</td>
<td>2.0</td>
<td>14</td>
</tr>
<tr>
<td>740</td>
<td>266</td>
<td>2.3</td>
<td>16</td>
</tr>
<tr>
<td>830</td>
<td>299</td>
<td>2.5</td>
<td>17</td>
</tr>
<tr>
<td>870</td>
<td>313</td>
<td>3.0</td>
<td>21</td>
</tr>
<tr>
<td>900</td>
<td>324</td>
<td>3.0</td>
<td>21</td>
</tr>
</tbody>
</table>

Specification: <34.5 kPa at 232 kg/hr.
Measured by: Bird, O'Reilly
Equipment used: Wika -30 in. Hg/ +30 psi gage, 1000 mL graduated cylinder; Pulsar quartz watch.

XI. COOLANT COMPATIBILITY

A complete drawing package was sent to NASA and was approved before construction began. Materials in contact with coolant consist of the following: stainless steel, nickel, Teflon, Kapton.

Magnet water specification at the NHMFL:

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
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<tbody>
<tr>
<td>Total dissolved solids (as CaCO₃)</td>
<td>50 ppb</td>
</tr>
<tr>
<td>Total silica (as SiO₂)</td>
<td>10 ppb</td>
</tr>
<tr>
<td>Sodium (as CaCO₃)</td>
<td>40 ppb</td>
</tr>
<tr>
<td>Resistivity</td>
<td>6 Megohm-cm</td>
</tr>
<tr>
<td>Dissolved Oxygen</td>
<td>0.02 - 0.03 ppm</td>
</tr>
</tbody>
</table>

XII. ATMOSPHERE

The MDF-BC1 will operate in the following atmospheres:
- 0.1 bar Argon
- 18-45 degrees Centigrade air with 40 - 90% relative humidity.

XIII. EXTERNAL FIELD

The field external to the magnet has been measured at the midplane 200 mm from the outside surface of the MDF-BC1 shielding.

| Required field:       | 3 kW |
|                       | 3 gauss max. |
| Measured field:       | 2.3 gauss |
| Performed by:         | Bird, Bole, Loffelbein |
IXV. PACKAGING

The MDF-BC1 is adequately packaged for damage-free handling. After operation it was drained and dried by blowing compressed air through it for approximately 3 hours. It was then filled with Helium gas and closed.

CONCLUSIONS

The magnet project was successfully completed. Additional magnets could be built if requested. The primary change that could be made to attain higher field and/or uniformity would be to make the magnet longer. However, for this first magnet, the overall length was constrained in the contract to be less than or equal to 238.1 mm. The NHMFL looks forward to receiving results of the tests to be performed at NASA.
NOTES:
1. REMOVE ALL BURRS AND SHARP EDGES
2. UNLESS OTHERWISE SPECIFIED MACHINE SURFACE GY
3. PLATE (0.013) THICK PER MIL-C-26074E
4. TFE TEAM (0.005±0.0017) THICK
5. ALL DIMENSIONS ARE AFTER PLATING AND COATING.
NOTES:
1. REMOVE ALL BURRS AND SHARP EDGES
2. UNLESS OTHERWISE SPECIFIED, MACHINE SURFACE \( \mathfrak{M} \)
3. NI PLATE 0.013 THICK PER MIL-C-26074E
4. TFEFLON COAT (0.05±0.0127) THICK
5. ALL DIMENSIONS ARE AFTER PLATING AND COATING.
NOTES:
1. REMOVE ALL BURRS AND SHARP EDGES
2. UNLESS OTHERWISE SPECIFIED, MACHINE SURFACE
3. NI PLATE 0.013 THICK, PER MIL-C-26074E
4. TEFILON COAT (0.0580.0127) THICK
5. THIS DIMENSION IS AFTER PLATING AND TEFLON COATING,
   ALL OTHER DIMENSIONS ARE PRIOR TO COATING.
NOTES:
1. REMOVE ALL BURRS AND SHARP EDGES
2. UNLESS OTHERWISE SPECIFIED MACHINE SURFACE
NOTES:
1. REMOVE ALL BURRS AND SHARP EDGES
2. UNLESS OTHERWISE SPECIFIED MACHINE SURFACE
3. MATERIAL: Cu 0.2 THICK
4. ELECTROLESS Ni PLATE 0.013 MAX THICKNESS EACH SIDE
PER MIL-C-26074E(10-12% PHOSPHORUS CONTENT)
5. TEFLOM COAT (0.055+0.0125) THICK, MASK AS INDICATED
NOTES:
1. REMOVE ALL BURRS AND SHARP EDGES
2. UNLESS OTHERWISE SPECIFIED MACHINE SURFACE
3. MATERIAL: TEFLOW, 1.0 THICK STOCK
NOTES:
1. REMOVE ALL BURRS AND SHARP EDGES
2. UNLESS OTHERWISE SPECIFIED MACHINE SURFACE
3. MATERIAL: TEFLOM, 1.0 THICK STOCK

REVISIONS

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<td>MFG RELEASE</td>
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NOTES:
1. REMOVE ALL BURRS AND SHARP EDGES
2. UNLESS OTHERWISE SPECIFIED MACHINE SURFACE
3. MATERIAL: TEFLO, 1.0 THICK STOCK

REVISES
ZONE REV DESCRIPTION DATE APPROVED
- INITIAL RELEASE
A ADDED "STOCK" TO NOTE J 13/12/95
B DISC C TO DISC B IN NAME 13/12/95
C CHNGD HOLE PATTERN AND DIMS 13/02/95
D MFG RELEASE 29/09/95
NOTES:
1. REMOVE ALL BURRS AND SHARP EDGES
2. UNLESS OTHERWISE SPECIFIED MACHINE SURFACE
NOTES:
1. REMOVE ALL BURRS AND SHARP EDGES
2. UNLESS OTHERWISE SPECIFIED MACHINE SURFACE

SECTION A-A

RADIAL/AXIAL GROOVES - SCALE 10:1
NOTES:
1. REMOVE ALL BURRS AND SHARP EDGES
2. UNLESS OTHERWISE SPECIFIED MACHINE SURFACE
3. MATERIAL: Cu 0.2 THICK
4. ELECTROLESS Ni PLATE 0.013 MAX THICKNESS EACH SIDE
   PER MIL-C-26074E (10-12% PHOSPHORUS CONTENT)
5. TEFLOM COAT (0.058-0.0127") THICK, MALK AS INDICATED

OUT TELFON COATING THIS FACE

OUT TELFON COATING THIS FACE
FLAT PATTERN LAYOUT
NOTES
1. REMOVE ALL BURRS AND SHARP EDGES
2. UNLESS OTHERWISE SPECIFIED MACHINE SURFACE 1/4
3. MATERIAL: TEFLOM

HOLE & NOTCH DETAIL - SCALE 5:1

SECTION A-A - SCALE 5:1

GENERAL TOLERANCES
1 PL DEG 0.25
2 PL DEG 0.10
ANGLES 0.1

MATERIAL:
INSDULATOR, SPACER, COIL A

SEE NOTE 3.

INSULATOR, SPACER, COIL A

RES/HOU-12-16
SCALE 1/1

1000 EAST PALM DRIVE
TALLASSADEGE, FLORIDA 32508-4005
NOTES:
1. REMOVE ALL BURRS AND SHARP EDGES
2. UNLESS OTHERWISE SPECIFIED MACHINE SURFACE
3. MATERIAL: TEFLOWN

HOLE/NOTCH DETAIL - SCALE 5:1

16X #2.50
2 PL (D AND D0)
SPACED AS SHOWN
50X #2.50

3.00 STOCK

SECTION A-A - SCALE 5:1

REVIEWS

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<td>B</td>
<td>A</td>
<td>CHNG D' NOTCHES TO 2.5MM DIAM.</td>
<td>18/12/95</td>
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<td>C</td>
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<td>CHNG D' HOLE PATTERN &amp; DIMS.</td>
<td>18/03/96</td>
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</table>
NOTES:
1. REMOVE ALL BURRS AND SHARP EDGES
2. UNLESS OTHERWISE SPECIFIED MACHINE SURFACE
3. MATERIAL: TEFLOM

HOLE/NOTCH DETAIL - SCALE 5:1

SECTION A-A - SCALE 5:1

16 X #2.50
3 PL. ID AND CO
SPACED AS SHOWN

SOC.10.0 A 4 6

50 X #2.50
EQUALLY SPACED
SOC.10.0 A 4 6

3.00 STOCK
NOTES:
1. REMOVE ALL BURRS AND SHARP EDGES
2. UNLESS OTHERWISE SPECIFIED MACHINE SURFACE
NOTES:
1. REMOVE ALL BURRS AND SHARP EDGES
2. UNLESS OTHERWISE SPECIFIED MACHINE SURFACE
NOTES:
1. REMOVE ALL BURRS AND SHARP EDGES
2. UNLESS OTHERWISE SPECIFIED MACHINE SURFACE
3. LOCATIONAL INTERFERENCE FIT (FN1) PER ANSI B4.2-1978
4. SHAFT DIA, 0.02 FIT, 6 PLCS, EQUALLY SPACED

MATERIAL:

a. 9.33(1/8") PLATE STOCK, 304L SS
b. 9.33(1/8") BAR STOCK, 304L SS
NOTES:
1. REMOVE ALL BURRS AND SHARP EDGES
2. UNLESS OTHERWISE SPECIFIED MACHINE SURFACE
3. MATERIAL: C10100, C10200, OR C11000, 0.2 THICK, HALF HARD
4. ELECTROLESS Ni PLATE 0.013 THICK PER MIL-C-26074E
   (10 - 12% PHOSPHORUS CONTENT)
5. # - BOLT CIRCLE DIAMETER
6. ^ - COOLING HOLE ANGLE

REVISIONS

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<td>19/12/95</td>
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<td>D</td>
<td>CHNGO MATERIAL AND Ni PLATE</td>
<td>27/12/95</td>
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<td>E</td>
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<tr>
<td>F</td>
<td>152 HOLS WAS 129 HOLES</td>
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<th>#B</th>
<th>#C</th>
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<tr>
<td>1</td>
<td>236.0</td>
<td>192.0</td>
<td>213.90</td>
</tr>
<tr>
<td>2</td>
<td>266.0</td>
<td>218.0</td>
<td>240.30</td>
</tr>
<tr>
<td>3</td>
<td>302.0</td>
<td>244.0</td>
<td>269.50</td>
</tr>
</tbody>
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ALL B.C. DIAMETERS ARE BASIC
SEE NOTE 5
NOTES
1. MATERIAL: PHILUX (L7022) 1.3 ML DULO
2. REVISIONS
   A
   B
   C
   D
3. NOTCH LOCATIONS
   - MEASURED FROM
   - MIN/MASS FLD WOODWORKING
   - INGLISH BITTER DISK
4. GENERAL TOLERANCES
   - Material to
   - Tolerances to
   - Marks and
   - Registration
5. THIRD ANGLE PROJECTION

THICKNESS

SPACE 25 FLANGE HDL